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EFFECT OF GROUND-GRID CHANGES ON CONTROL-CABLE VOLTAGES AT BRUCE NGS "B"

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Because of lightning-related electrical interference problems associated with power and control cables running between the Bruce "B" powerhouse and standby generators SG5 and SG6, additional bonding conductors were installed to supplement the existing ground mat in this area. The effectiveness of the supplementary bonding wires was tested by injecting variable-frequency and broadband current signals into the ground mat and measuring the resulting transferred voltages and currents on a selected annunciation cable before and after the wires were connected. Results are presented showing that the cable conductors may have flashed over to ground and that the bonding wires have a beneficial effect on transferred voltages and currents.

1.0 INTRODUCTION

On August 4th and October 15th, 1989, while thunderstorms were in progress, numerous electrical and instrumentation faults appeared on units 0 and 5 of Bruce NGS "B". Consequences included the temporary unavailability of critical standby generators, unwarranted station service transfers, and fuse blowing on dc supply wiring.

An investigation of these events appeared to implicate the control and annunciation cables running between the powerhouse and standby generators SG5 and SG6 located between the intake and outflow channels at the south end of the station. The actual mechanism is not clear, but a plausible hypothesis is that a lightning stroke in the vicinity of the generators produced a large ground potential difference (GPD) between these buildings and the powerhouse, and that the GPD in turn produced voltages and currents on the cables sufficient to cause electrical interference or even flashovers between the terminal equipment and local ground potential. According to this hypothesis, the installation of additional, appropriately placed, bonding conductors to the station ground mat could alleviate the problem.

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This report describes some field tests that were performed to determine the effect of adding additional bonding conductors on the GPD and on the voltages and currents appearing on a selected cable.

2.0 SITE DESCRIPTION

Figure 1 shows the physical layout of the standby generators, SG5 and SG6, the powerhouse, and the nearby grounding conductors. The standby generators and the adjacent oil storage tanks have a conventional perimeter ground that is bonded to the powerhouse ground by two buried conductors. In addition, the buildings are encircled by grounding conductors running along the intake channel, across the water recirculation duct, and back along the discharge channel.

Power and annunciation cables run between each of the standby generators and the power house in underground cable ducts; the power cables terminate at switchgear cubicles in unit 5, while the annunciation cables continue on to the Control Equipment Room (CER) in unit 0. The overall length of the annunciation cables is about 520 m (1700 ft.).

The power cables are contained in 10.2 cm (4-inch) PVC ducts together with a "green wire" ground, and the cable sheaths are single-point grounded at the generator buildings. The annunciation cables are run in 10.2 cm steel ducts without a ground wire, and the cable shields are grounded at the CER.

3.0 TEST PROCEDURE

Prior to the tests, station personnel pulled two 253 mm^2 (500 mcm) bonding conductors through spare ducts adjacent to the annunciation cables between the powerhouse and SG5 and SG6 respectively. A third 253 mm^2 conductor was laid between SG5 and the control gate in the water recirculation duct. These conductors were left unconnected for the initial measurements. Subsequent tests were performed with the two power house bonds connected and with all three bonding conductors connected.

In order to simulate the effect of a lightning stroke in the vicinity of the standby generators, signal generators were connected to the ground mat in SG5. A return path for the current was provided by running a cable (4-AWG #6 conductors in parallel) from SG5 across the forebay channel to the southwest corner of the switchyard ground grid.

Tests were performed by impressing continuous-wave sinusoidal (frequency domain) voltages and fast-rise step (time domain) voltages into the ground system. Voltages and currents were measured on the SG5 terminations of the following conductors: (a) the source circuit, (b) a sensing wire connected to the ground grid in the vicinity of the oil storage tanks (see Fig 1), (c) the shield of one 50 pair annunciation cable, and (d) a selected wire pair within the same cable that had been grounded at the remote end. The frequency domain responses are normalized to unit injected current at each frequency. Test equipment is itemized in Table I.

Electrical schematics of the test arrangement are shown in Figures 2(a) and 2(b). In Figure 2(a), ground mat and conductor impedances are represented by Z_A to Z_F, and the optional ground connections on the cable shield, the powerhouse bonds, and the recirculating gate bond wire are represented by switches S_1, S_2, and S_3 respectively. Figure 2(b) shows the manner of connecting the network analysers to the conductors; by using the dual inputs, both amplitude and phase of the measured quantity relative to the injected current could be measured. Phase information helps to identify resonances at the higher frequencies.

TABLE I

EQUIPMENT USED FOR TESTS

(a) Frequency Range 0.01 to 50 kHz.

Hewlett Packard network analyser model 3766
Crown/Macrotech audio frequency amplifier model 2400
Tektronix oscilloscope model 2430A

(b) Frequency Range 0.01 to 10 MHz

Hewlett Packard network analyser model 3570A
Hewlett Packard synthesizer model 3330B
ENI radio-frequency amplifier model 240L

(c) Impulse signals

Haefely impulse generator model 48
Tektronix oscilloscope model 2430A

4.0 RESULTS

4.1 Source Circuit Impedance

The source circuit impedance (source voltage divided by injected current) was measured between 0.1 and 50 kHz at the start of the tests. The results, shown in Figure 3, indicate that the circuit is essentially inductive between 100 Hz and 40 kHz.

Note: Data from the low-frequency measurements are somewhat limited due to the tendency of power-frequency voltages and currents on the conductors to overload the amplifiers and detectors.

4.2 Effect of Added Bonding Conductors

(a) On Sense Wire Voltage

The sense wire measures the transferred voltage (a combination of GPD and frequency-dependent induced voltage) from the oil tank reference point. Figures 4(a) and 4(b) show measurements of the transfer impedance (transferred voltage divided by injected current) before and after the three bonding wires were installed, respectively. The transfer impedance is also inductive up to about 40 kHz, showing that the transferred voltage is proportional to the source voltage in this region. A broad resonance-type variation at about 0.6 Mhz probably represents a quarter-wave response of the sense wire.

The bonding wires produce a frequency dependent reduction in the transferred voltage ranging from about 50% at 10 kHz to a negligible amount at 60 kHz. For frequencies between 1 kHz and 1 Mhz, the ground impedance in this area of the station can be modelled as 9 μH in parallel with 2 Ω, with the bonding wires contributing an additional 11 μH in shunt.

(b) On Cable Shield Voltage

Figures 5(a) and 5(b) show the open circuit voltage between the end of the annunciation cable shield and the SG5 equipment cabinet ground (the transferred voltage from the powerhouse) per unit of injected current, before and after the bonding wires were connected. This transfer impedance is inductive up to about 10 kHz, displays two maxima at 15 kHz and 40 kHz, and then decreases with further increases in frequency.

The three bonding conductors produce a frequency dependent reduction in the shield voltage per unit current, ranging from about a factor of 5 between 100 Hz and 10 kHz, to a negligible amount at 60 kHz.

A similar result is found in the response of the cable shield voltage to a fast-rise current impulse injected into the ground grid, as shown in Figures 6(a), 6(b), and 6(c). These figures show oscillographic (time domain) representations of the injected current and the shield voltage without the additional bonding wires, with the two additional powerhouse bonds connected, and with all three bonding wires connected. The characteristic frequency is about 15 kHz. The peak shield voltage per unit injected current is reduced by a factor of 1.75 due to the powerhouse bonding wires and by a further factor of 1.9 due to the recirculating gate conductor, for an overall reduction by a factor of 3.3.

(c) On Cable Shield Current

The shields of the annunciation cables are installed for electrostatic shielding only, and are not intended to carry current. The "green-wire" grounding connections at the powerhouse cable distribution frame (CDF) consist of small diameter (possibly AWG no. 14 or 16) hook-up wire typically covering a distance of 1 to 3 m in parallel with other unshielded conductors before reaching the CDF ground bus.

Current will flow on the cable shield, however, if the cable is exposed to resonant frequencies or in the event of a flashover between the ungrounded cable shield termination and local cabinet ground. The magnitude of the shield current per unit injected current, measured with the shield termination shorted to cabinet ground, is shown in Figures 7(a) and 7(b). This current transfer function is relatively independent of frequency up to about 15 kHz and then shows a moderate decrease with further increases in frequency.

With the three bonding conductors installed, the shield current is reduced by a factor ranging from about 5 at 1 kHz to essentially zero at 60 kHz.

(d) On Cable Core Voltage

Cable core voltages were measured on a spare pair that was open-circuited at the SG5 end and grounded at the remote (CER) end of the cable. Cable pairs that are connected to terminal equipment may have different impedances to local ground as a result of equipment loading, and could give different results.

Figure 8(a) shows the ratio of pair voltage to open-circuit shield voltage. The ratio is essentially unity up to several hundred kHz except for a cable resonance at 80 kHz, indicating that the pair-to-ground and shield-to-ground transfer impedances are the same when the shield is grounded at one end only. Conversely, if the cable shield is grounded at both ends, the pair-to-ground voltage is reduced at most frequencies by the neutralizing action of the shield current as shown in Figure 8(b).

5.0 SELF AND TRANSFER IMPEDANCE OF CABLE SHIELD

Additional frequency-domain measurements of interest in the analysis of shielded cable response to broadband electrical disturbances are the effective self impedance of the cable shield (the ratio of the open-circuit voltage to the short-circuit current) and the apparent shield-to-core transfer impedance (the pair voltage divided by the shield current, both measured with the shield grounded at both ends). These quantities are graphed in Figures 9(a) and 9(b).

6.0 DISCUSSION OF RESULTS

The present tests were performed to evaluate the effectiveness of additional ground conductors in reducing lightning-related voltages on an annunciation cable running between the Bruce "B" powerhouse and standby generators SG5 and SG6. The results show that the additional conductors will significantly reduce voltage stresses on the cable. Some more specific observations are given below.

1. The station ground mat between SG5 and SG6 and the powerhouse appears to be adequately represented by lumped resistive and inductive components up to about 40 kHz. A broad resonance type response at 15 kHz seen on the long cable but not on the shorter sense wire, corresponding to a quarter-wave length in earth of about 4 km, could be due to reflections from remote grounding mismatches or to unspecified capacitive loading of cable pairs.

2. Without the additional bonding conductors, the voltage per unit injected current between the open end of the cable shield and cabinet ground in SG5 has a maximum value of 2.5 V/A at 40 kHz and falls off at higher and lower frequencies. Pair-to-ground voltages are of similar magnitude. Therefore, a lightning stroke that injects a current of 10 kA can lead to transferred voltages of the order of 20 kV, and pair-to-ground or shield-to-ground flashovers are a very real possibility in the event of a lightning strike close to the standby generators.

3. Without the additional bonding conductors, up to 10% of the stroke current may flow along the cable shield or core conductors to the powerhouse ground in the event of a flashover at the SG5 cable termination. The cable installation is clearly not designed to carry this kind of current. Given the length of shared cable runs, the long "green-wire" grounding connections at the cable distribution frame, and the exposure of unshielded wire pairs on the CDF, serious interference with other circuits is a real possibility.

4. The additional bonding conductors reduce the cable shield voltage and pair voltages by a factor ranging from 5 at the low frequency end to essentially zero at 60 kHz. The overall reduction for a broadband pulse is a factor of about 3. Because of this reduction, pair or shield to ground flashovers are less likely and, if they occur, the current flowing on the conductors will be reduced by a similar factor.

5. Above 60 kHz, the responses of the ground system and the cable to broadband electromagnetic disturbances are complex and not well understood. Further work will be required to develop effective methods of reducing transferred voltages and currents in this frequency region.

6. The cable shielding and grounding practices presently employed in the powerhouse are not designed to handle broadband electromagnetic disturbances such as those produced by lightning, and provide no protection against them. Cables that are exposed to these disturbances may require additional protection, either from improved grounding and bonding practices in the exposed areas, or from additional shielding measures on the cables themselves.

7.0 CONCLUSIONS

With the original grounding, transferred voltages up to 20 kV can be expected between cable shield and core conductors and cabinet ground in SG5 and SG6 in the event of a lightning strike close to the buildings. If flashovers occur, up to 10% of the stroke current can flow along the cable conductors to the Control Equipment Room in the powerhouse. With the additional bonding conductors installed, voltage stresses produced on the cable installations by broadband lightning-type disturbances are reduced by a factor of about three.

More work is required to improve our understanding of ground grid performance at high frequencies, and to provide more protection for powerhouse cables that are exposed to the outside environment.

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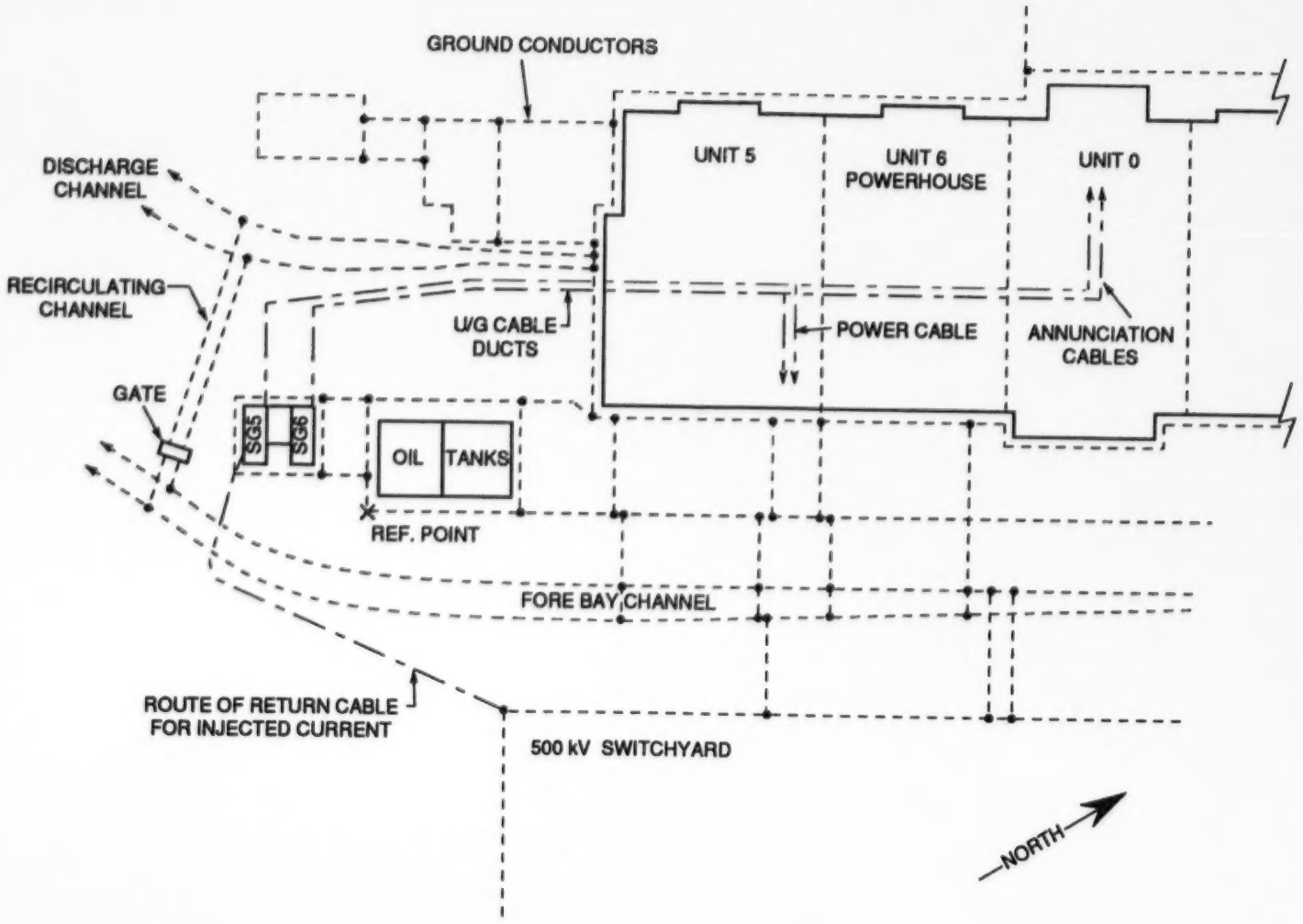
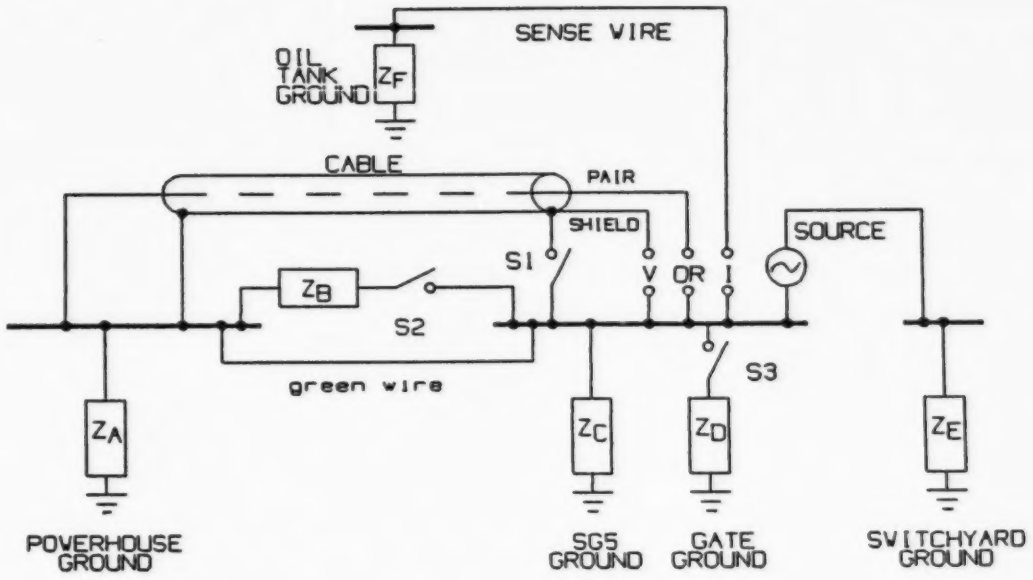
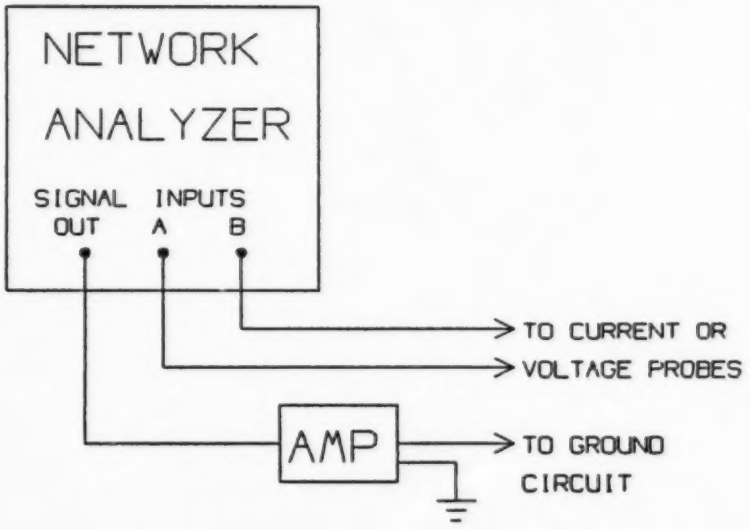


FIGURE 1. BRUCE "B" LAYOUT SHOWING GROUNDING CONDUCTORS



(a) System under test



(b) Network analyser connections

Figure 2: Electrical Schematics of Test Arrangement.

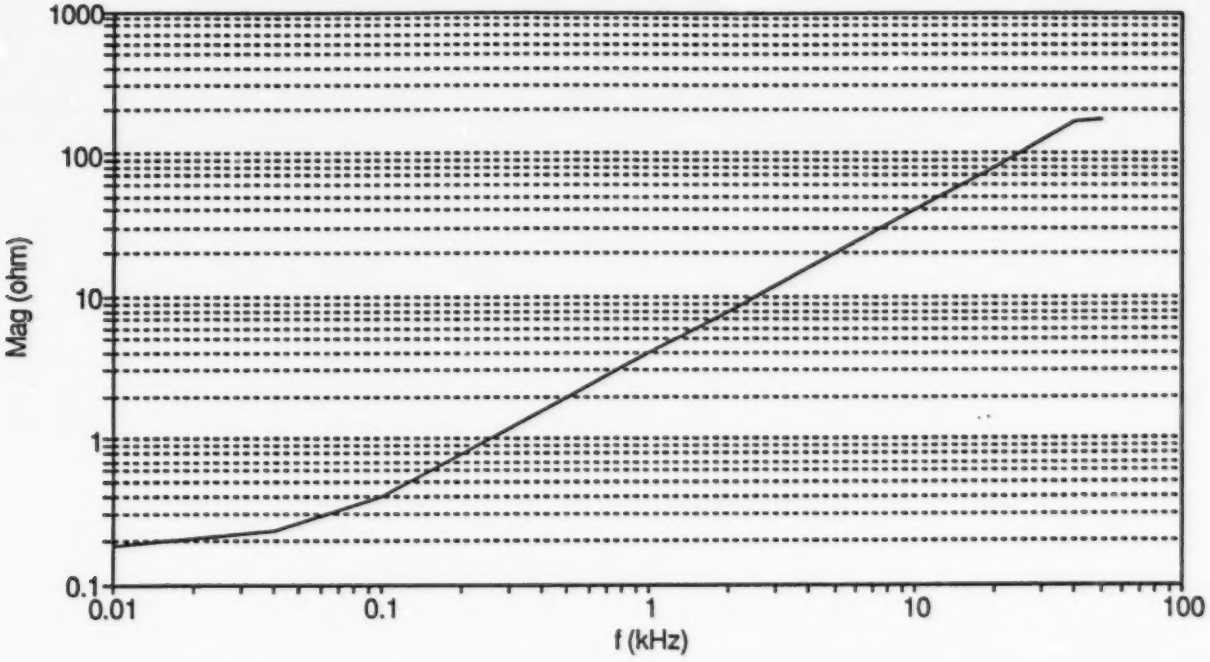
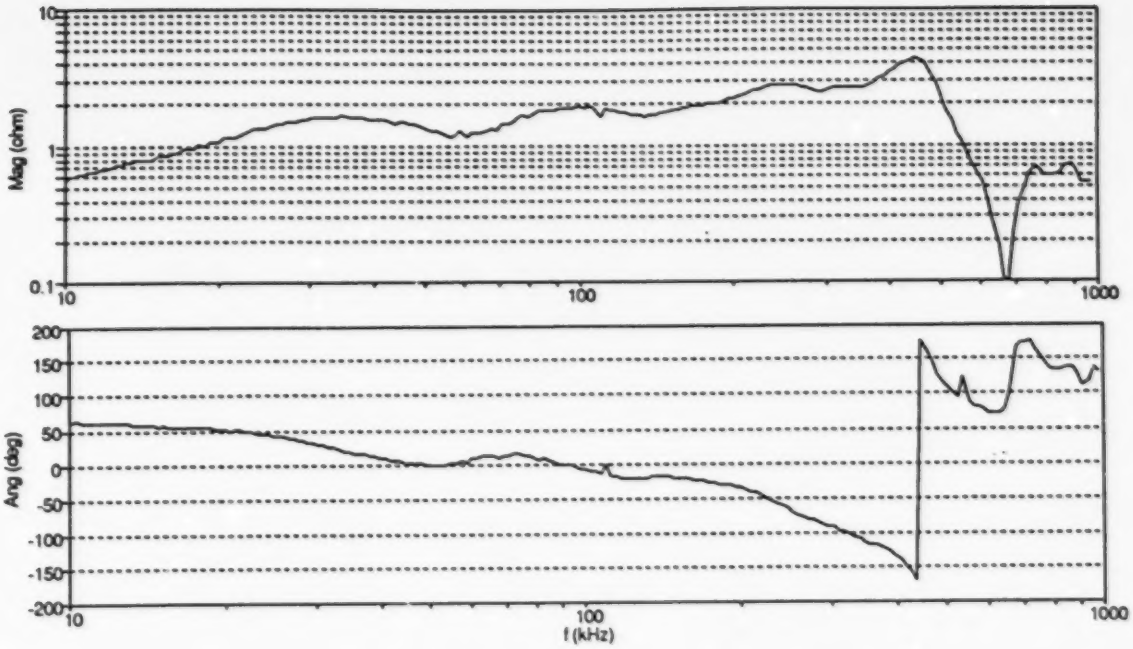
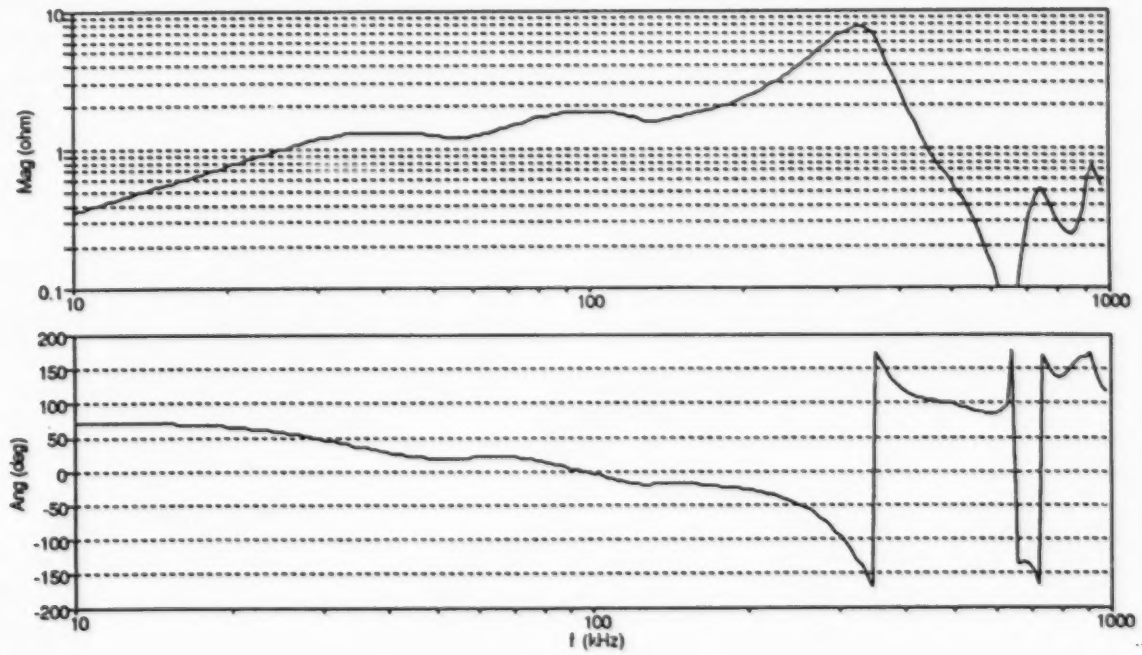


Figure 3: Impedance of Current Injection Circuit.

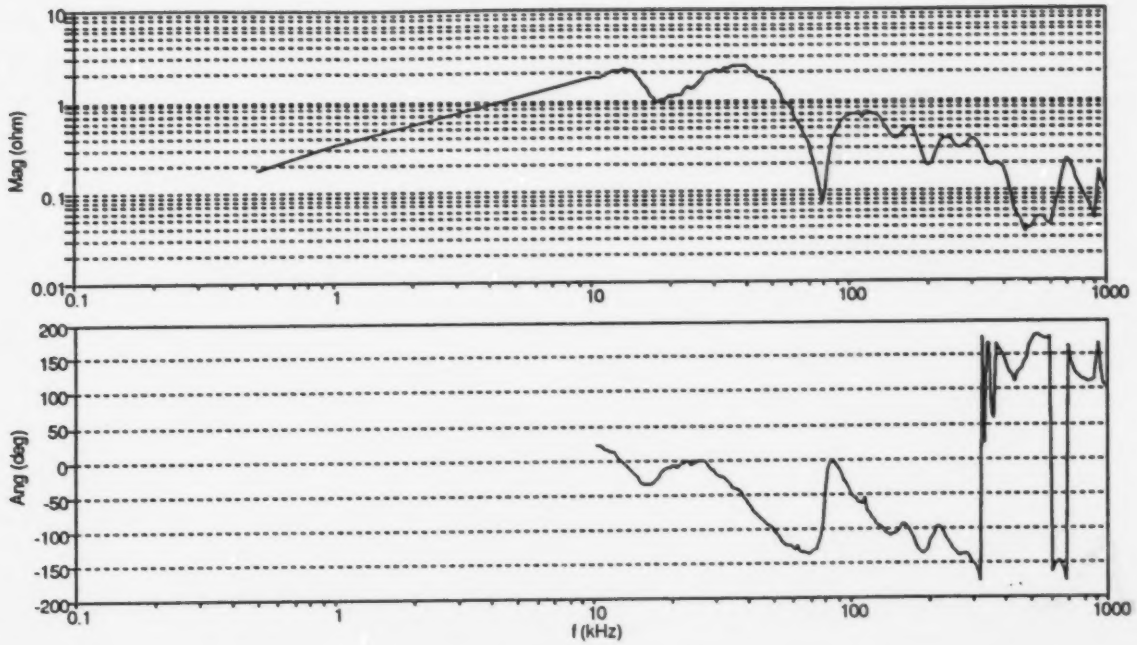


(a) Original grounding

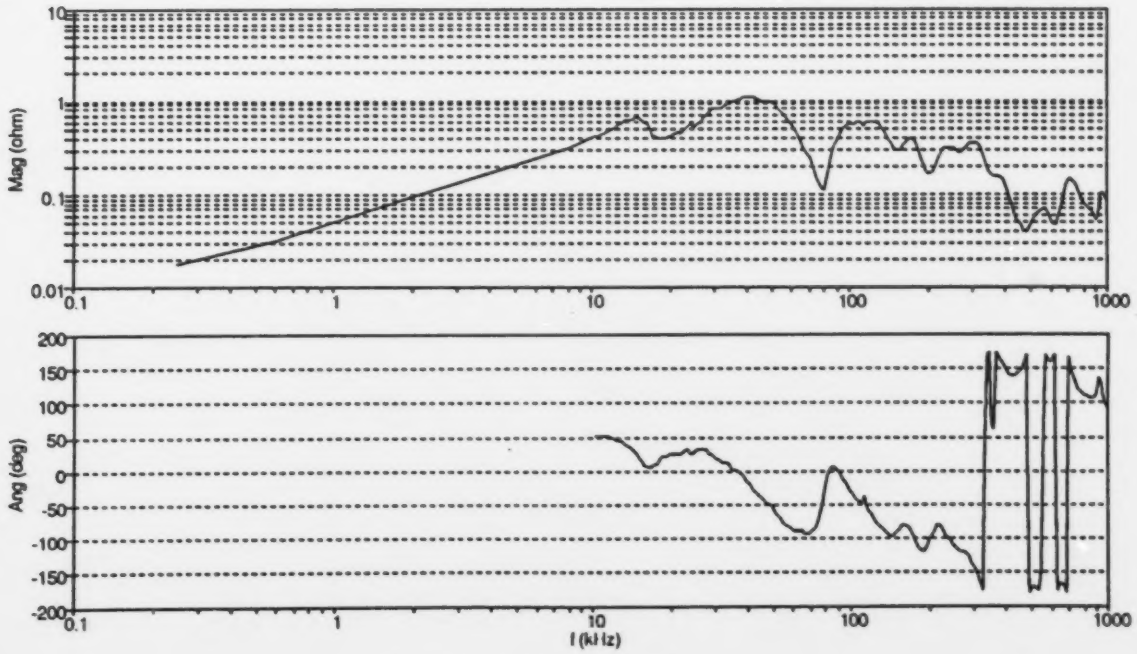


(b) With additional bonding wires

Figure 4: Amplitude and Phase of Voltage on Oil-tank Sense Wire.

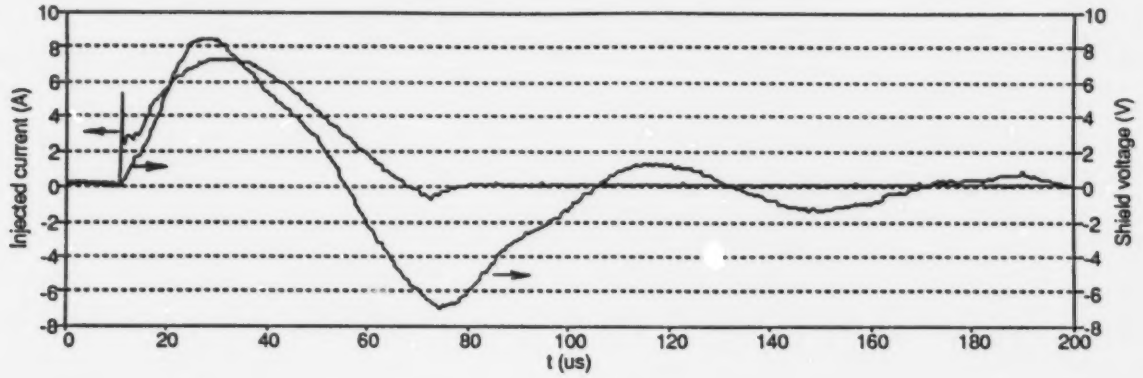


(a) Original grounding

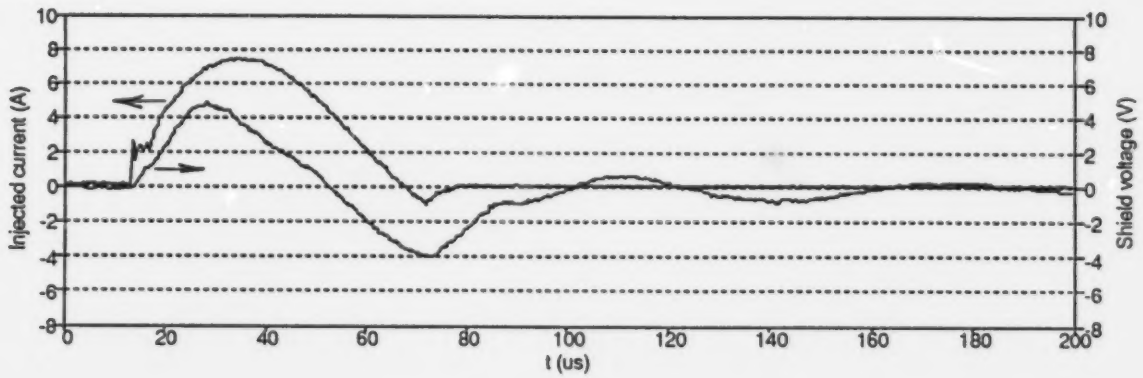


(b) With additional bonding wires

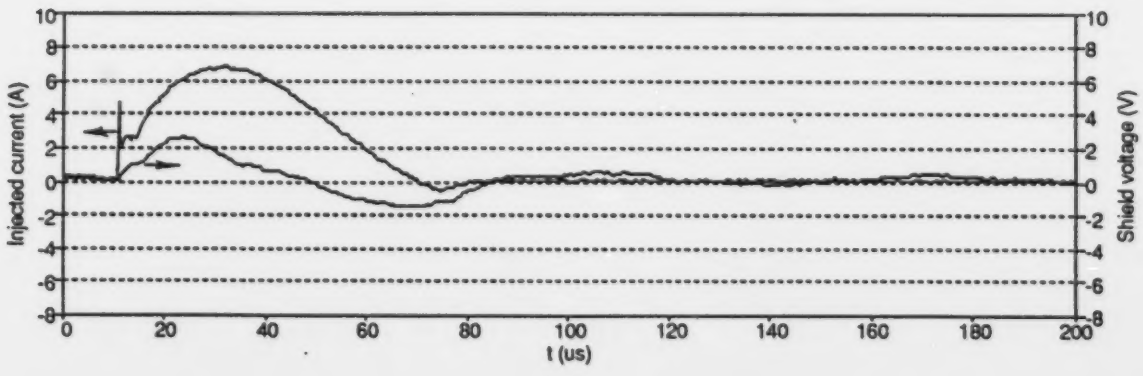
Figure 5: Amplitude and Phase of Voltage on Annunciation Cable Shield.



(a) Original grounding

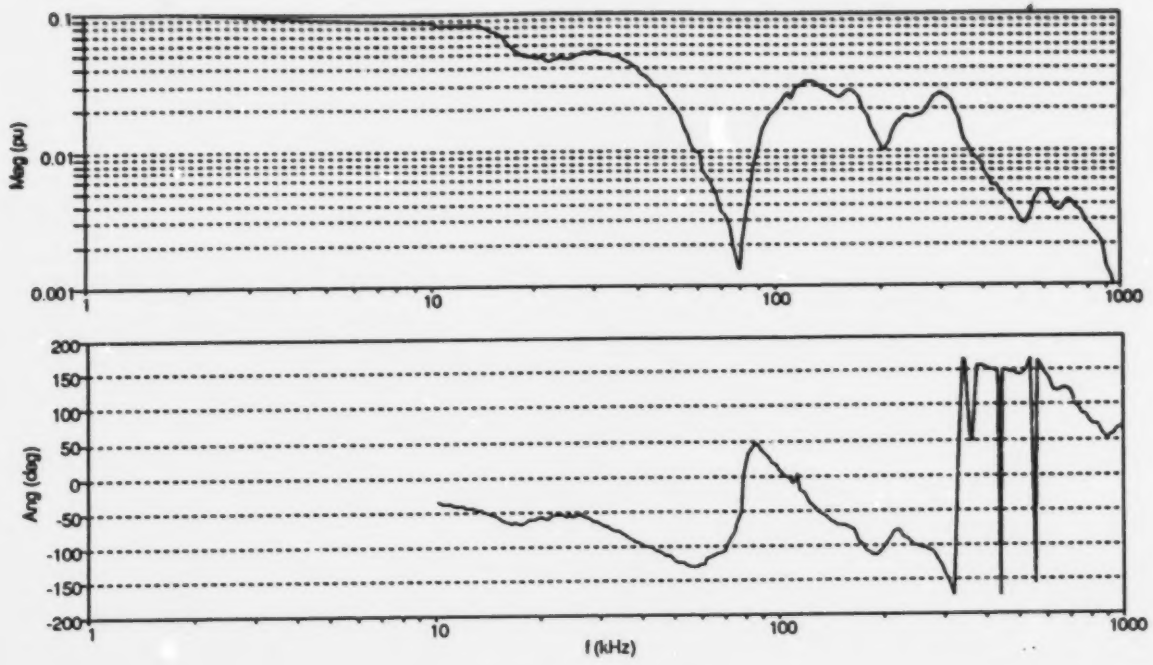


(b) With powerhouse bonding wires

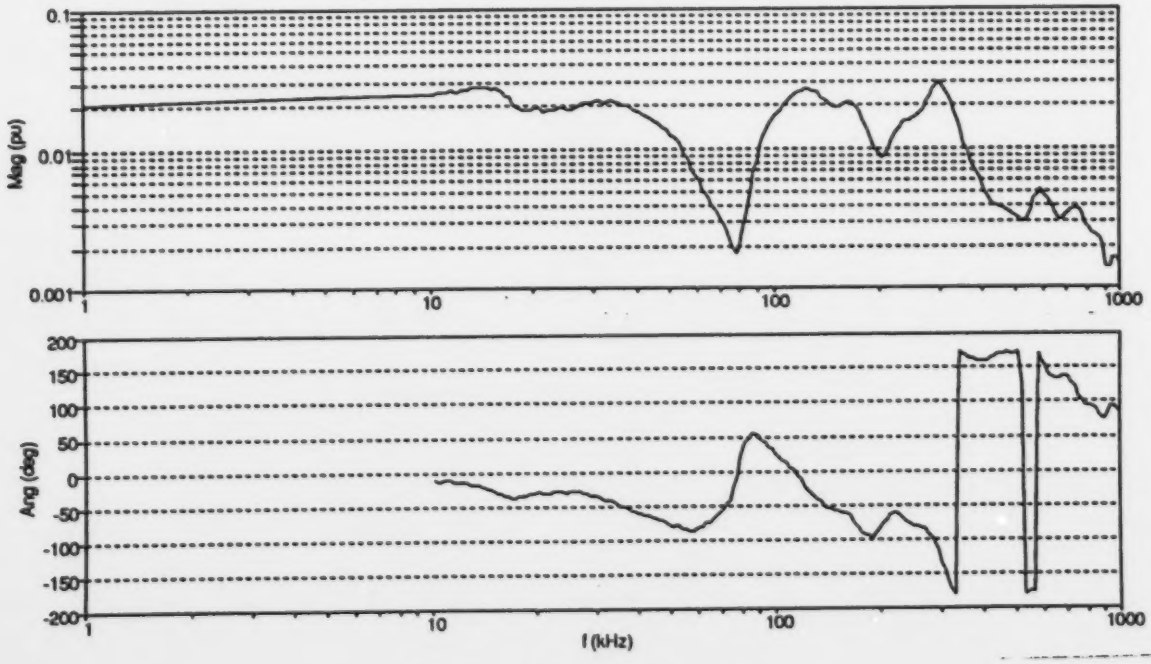


(c) With powerhouse and gate bonding wires

Figure 6: Injected Current and Shield Voltage Waveforms.

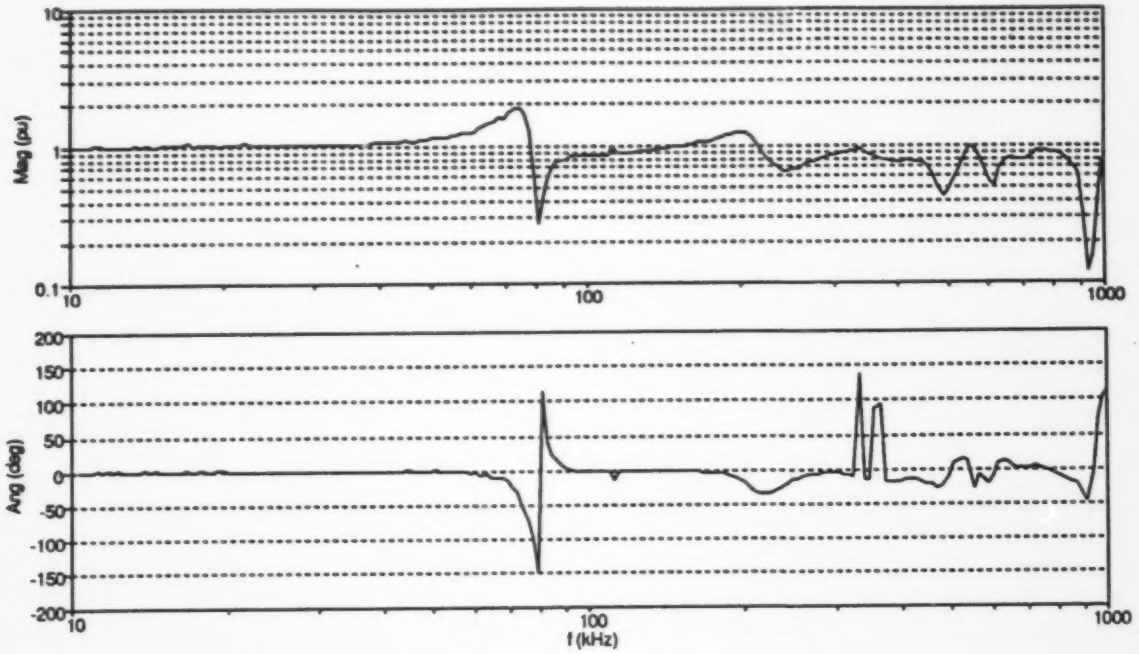


(a) Original grounding

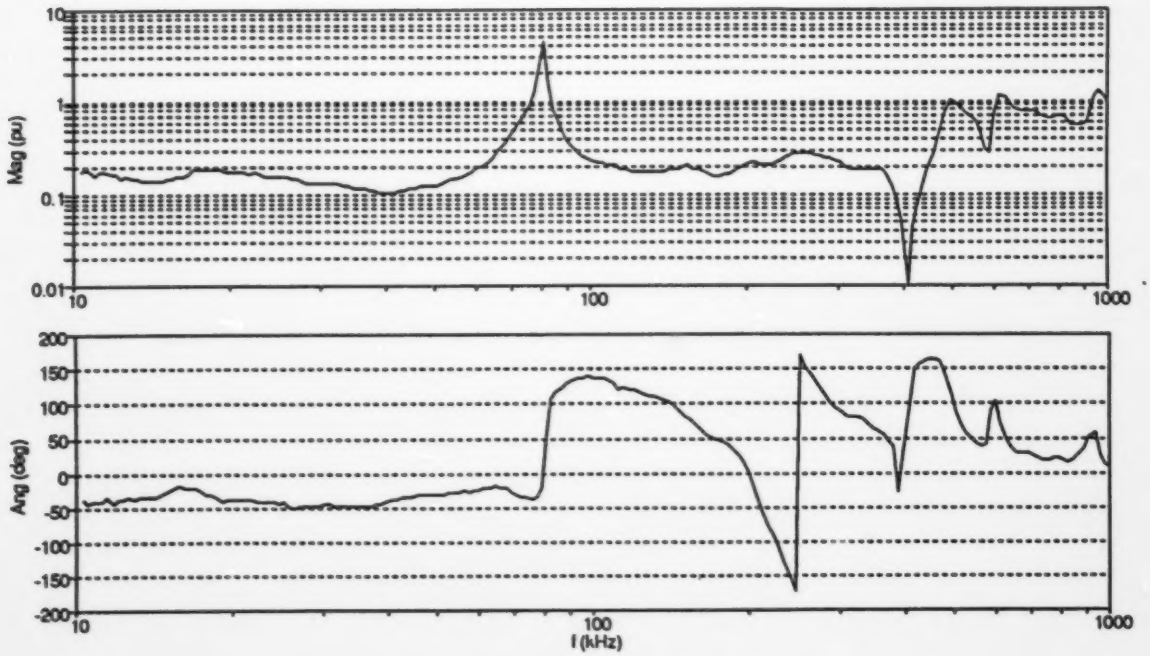


(b) With additional bonding wires

Figure 7: Amplitude and Phase of Current on Annunciation Cable Shield.

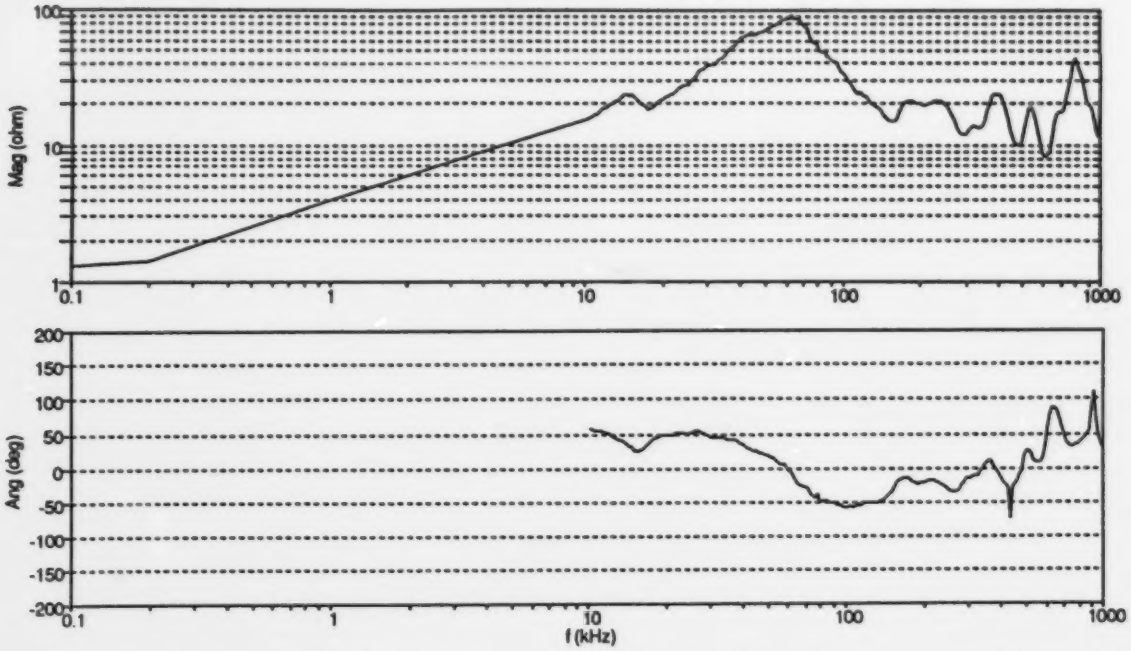


(a) Normalized to open-circuit shield voltage; no shield current

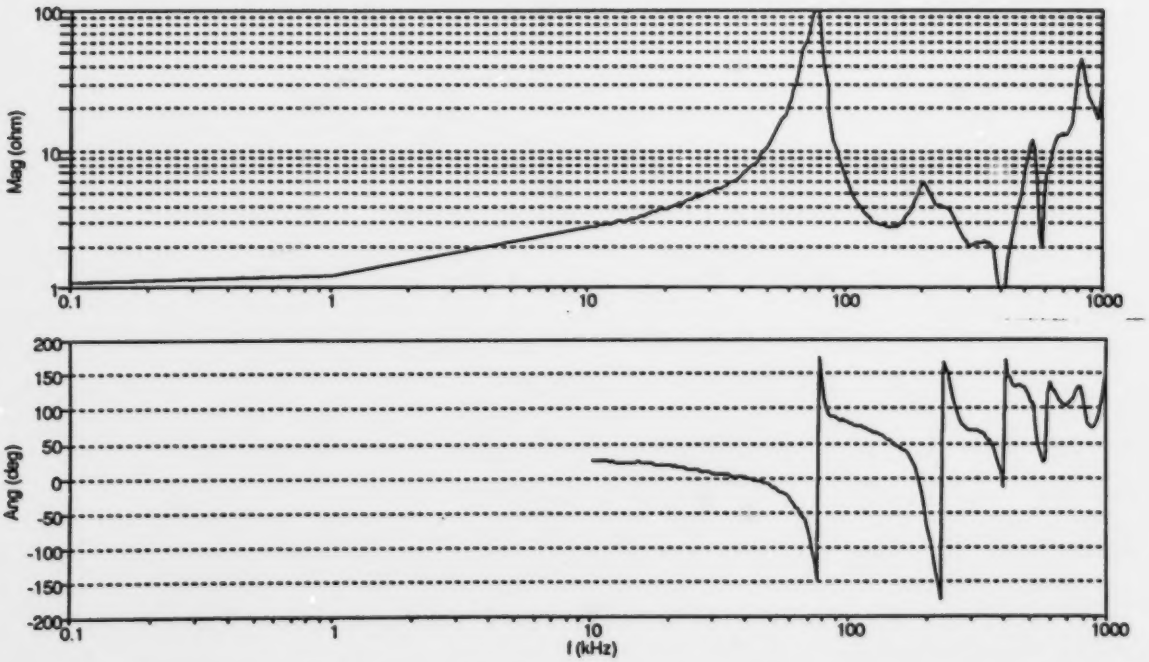


(b) Reduction from (a) due to shield current

Figure 8: Amplitude and Phase of Cable-Pair Terminal Voltage.



(a) Effective self impedance of cable shield



(b) Apparent shield-to-core transfer impedance

Figure 9: Amplitude and Phase of Selected Cable Transfer Functions.